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ENGINEERING MODELS OF BALLISTIC PERFORATION AT HIGH VELOCITIES.(U)
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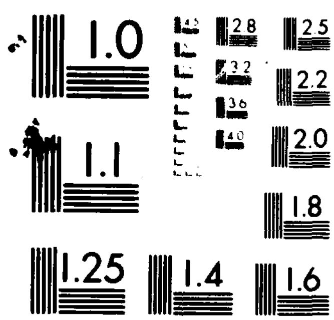

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20. Abstract

This report presents the results of ballistic tests consisting of 10 shots of long rod penetrators, made from SAE 4140 steel, on target plates: 50.8mm and 75.0 mm thick RHA, and 133.5mm 5083 H-115 aluminium. Impact and residual velocities as well as residual length of the penetrator have been measured. The target plates were sectioned and etched around the perforation cavities and subjected to close inspection. Mechanical properties of penetrator and targets were measured and a split Hopkinson pressure bar arrangement has been set up.

A new five stage engineering model of perforation of a metal target by a rigid projectile has been developed which does not rely on empirical factors.

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Abstract

This report presents the results of ballistic tests consisting of 10 shots of long rod penetrators, made from SAE 4140 steel, on target plates: 50.8 mm and 75.0 mm thick RHA, and 133.5 mm 5083 H-115 aluminium. Impact and residual velocities as well as residual length of the penetrator have been measured. The target plates were sectioned and etched around the perforation cavities and subjected to close inspection. Mechanical properties of penetrator and targets were measured and a split Hopkinson pressure bar arrangement has been set up.

A new five stage engineering model of perforation of a metal target by a rigid projectile has been developed which does not rely on empirical factors.

The main effort during this period was devoted to detailed examination of the results of a series of ballistic tests. These tests consisted of 10 shots of specially prepared long rod penetrators made from SAE 4140 steel (Note: not SAE 4340 steel as erroneously reported in the previous Annual Technical Report of Sept. 1979) on target plates of homogeneous armor steel (RHA) and 5083-H115 aluminum alloy. Thicknesses of the RHA plates were 75.0 mm and 50.8 mm and the aluminium target consisted of 3 plates in contact, each of 44.5 mm, for a total thickness of 133.5 mm. Impact was normal to the plate with impact velocities ranging from 1356 to 1560 m/s. Eight of the shots were successful in supplying useful information.

The tests were conducted in a well instrumented ballistic range which provided pre-impact velocity measurements by photo-cells and X-ray photographs of the projectile immediately prior and after perforation by flash radiographic equipment. After completion of the ballistic tests, the target plates were sectioned and etched around the perforation cavities which were then subjected to close inspection. Mechanical property tests were also made on the projectile and target materials. Since the perforation process occurs at very high rates of loading, mechanical properties at those rates would be useful in the analytical modelling. This data can be obtained by means of a split Hopkinson pressure bar (Kolsky bar).

A split Hopkinson pressure bar arrangement for longitudinal loading has been built. The loading is achieved by firing a short cylinder against the free end of the loading bar. Instead of using an air gun to drive the projectile, a rifle whose barrel was replaced by a thick walled cylinder (3/4"ϕI.D.) is being used. The velocity of the projectile, which is controlled by varying the amount of powder in the cartridge, is measured just prior to impact by a photocell. Plane impact is ensured by inserting the (1/2"ϕ) loading bar slightly into the barrel where the projectile is still guided.

Most of the experimental work with the Hopkinson bar until now has been to eliminate the noise from the measuring system. These efforts seem to have been successful and the recorded pulses are fairly "clean".

A second type of Hopkinson bar; a torsional or Kolsky bar, is being built. It has a simple loading device for introducing the torque into the loading bar and is expected to be ready for use during the coming year of research.

The output signals from the strain-gauges bridges are recorded in a digital oscilloscope (Explorer II, by Nicolet). Presently the signals are transferred to an XY recorder to be analyzed manually. A proper interface has been ordered recently (IEEE-488), which will enable us to transfer the recorded pulse directly from the oscilloscope to a minicomputer for further analysis.

When the measured residual velocities following perforation are extrapolated to zero by an analytical procedure, an estimate could be obtained for the ballistic limit velocity, V_L, for the projectile and the various target plates. For the steel plates, V_L for the 75.0 mm thickness was obtained to be 1325 m/s, while that of the 50.8 mm steel target plate was V_L = 1150 m/s. In the case of the aluminium targets, the test data was not sufficient for a reasonable estimate of V_L.

Some of the more important results of the various tests and examinations are attached to this report as an Appendix. The attached figures and tables consist of the following:

Fig. 1 - Geometry of projectile of SAE 4140 steel.

Table I - Penetrator: Material composition.

Table II - Penetrator: Mechanical properties.

Table III - Target plates: Mechanical properties.

Table IV - Projectile velocity characteristics prior to impact.

Table V - Contact time, residual velocity, and physical and geometrical characteristics after perforation.

Table VI - Dimensions of projectile entrance and exit holes in the target plates.

Figs. 2,3 - Cavity profiles in steel target plates showing hardness (R_c) measurements.

Fig. 4 - Cavity profile in an aluminium target.

Fig. 5 - Hole profile after perforation of 50.8 mm RHA target.

Fig. 6 - Hole profile after perforation of 75 mm RHA target.

Fig. 7 - Hole profile after perforation of 133.5 mm AL 5083 H-115 target.

Fig. 8 - Hole profile after perforation of 133.5 mm AL 5083 H-115 target.

Fig. 9 - Characterization of the final deformation and hole dimension for Table VII.

Table VII - Characteristic parameters measured for defining the final target deformation.

This examination of the results of the ballistic tests is intended to serve as a physical basis and motivation for the development of an engineering model of the perforation process at high impact velocities. The test results, especially the residual velocities and residual projectile lengths, will also serve as reference data for subsequent comparison with analytical predictions. The model would include the effects of erosion of the projectile and of plastic deformation and inertia of the projectile and target.

At the present time, a new five stage engineering model of perforation of a metal target by a rigid projectile has been developed. The initial stage relies on an assumed velocity field for a plastically deforming medium with a moving boundary (the indenter), where the unknown parameters are determined from the upper bound theorem of plasticity modified to include dynamic effects. Subsequent deformation stages include the development of a bulge at the rear surface of the target, the extension of the bulge, the development of a plug and a shear zone, and the ejection of the projectile and plug following material failure. This model is an improvement over that of Awerbuch and Bodner as it does not rely on any empirical factors and is more suitable for extension to the case of projectile erosion.

A paper describing this model is presently being prepared for publication (by Ravid and Bodner).

The personnel who worked on the research program during this period are: - Prof. S.R. Bodner, Assoc. Prof. J.M. Lifshitz, and Mr. Moshe Ravid and Mr. Ezra Scher, graduate students.

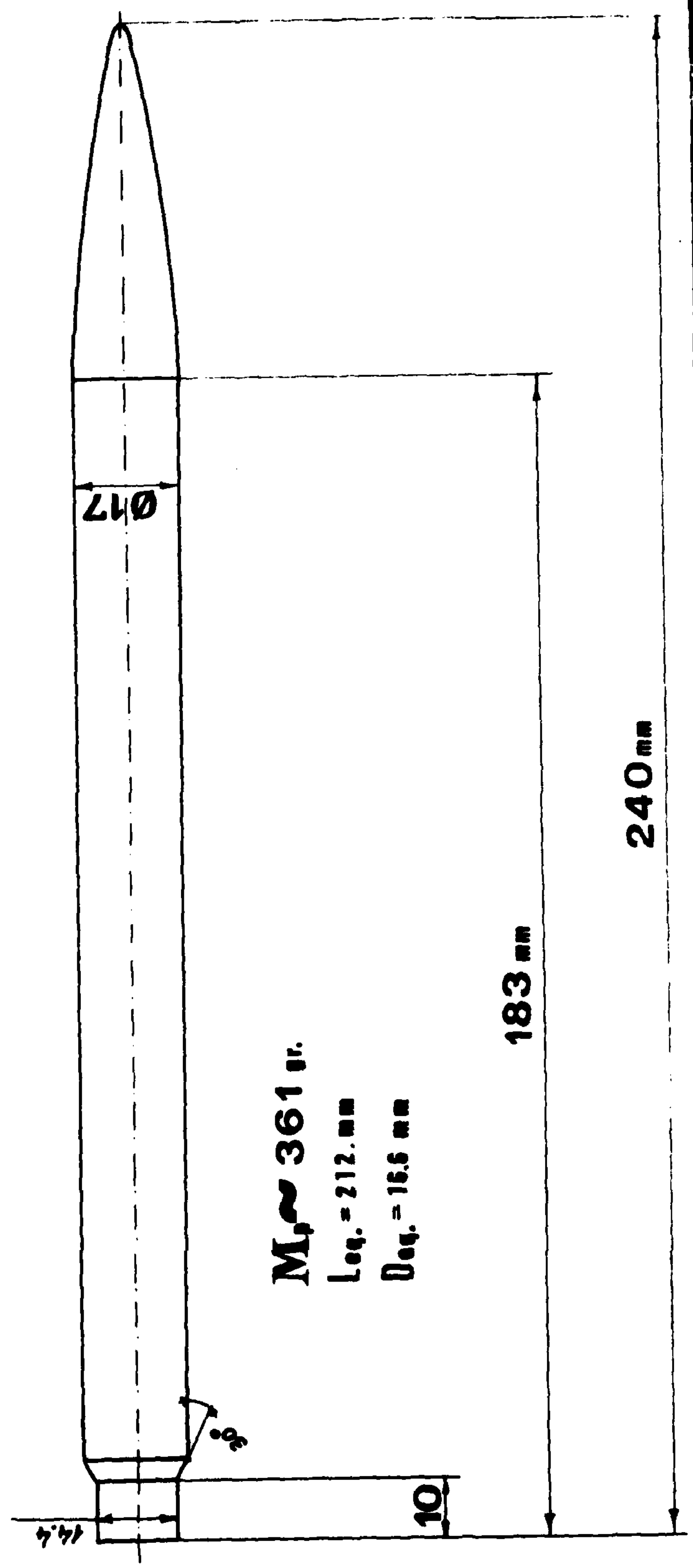


Figure 1 : STEEL S.A.E - 4140 PENETRATOR

Table I : Penetrator Material Description. SAE 4140 [EN 19A]

Symbol	C	Si	Mn	P	S	Cr	Mo
[%]	0.41	0.21	0.72	0.015	0.022	1.06	0.22

Table II : Mechanical Properties of Penetrator Material.

Yield Stress Y_p	Ultimate Stress U.T.S.	Elongation ϵ_{max}	Impact Test IZOD
Kg^f/mm^2	Kg^f/mm^2	%	$Kg^f \cdot m$
78 - 80	90 - 91	22 - 24	11 - 13

Table III : Target Plates and Mechanical Properties of Target Material.

Plate Material	Plate Thickness	Mechanical Properties - (*)		
		Yield Stress	Ultimate Stress	Max. Strain
	T	$Y_p(\sigma_{0.2})$	U.T.S.	ϵ_{max}
	mm	Kg^f/mm^2	Kg^f/mm^2	%
R.H.A.(**)	50.8	86	97-98.7	15.1-15.3
R.H.A.(**)	75	80-85	91.3-98.6	15.3
AL-5083 H-115	44.5	11-12	26.2-28.2	15.8-18.3

(*) At Strain-Rate of $\sim$0.1 Sec^{-1} for Steel and $\sim$0.6 Sec^{-1} for Aluminum Plates(obtained on M.T.S. machine, 25 ton capacity).

(**) Acc rding to M l-S-12560B (ORD)

Table IV : Summary of Before Target Penetration Results and Analysis.

Round Number	Target Descrip- -tion.	Striking Velocity (m/sec)		V_S	Trajectory Components (Degree)		Impact Angle (Degree "Nato")	Yaw Components (°) (Degree)		Yaw Angle (Degree)
		Photo- -electric Cell Results	Flash X-ray Average Results	Mean Striking velocity	Horizon- -tal	Vertical		Horizontal	Vertical	
11	75 mm	1560	1550	1555	-0.29	0.87	~1	0.22	0.04	0.23
12	R.H.A.	1430	1454	1442	-	0.74	~1		0.25	~0.3
13		1357	1355	1356	-0.06	0.82	~1	-0.55	-0.6	0.7
14	50.8mm	1560	1549	1555	-0.31	-	~1	0.74	-	~0.8
15	R.H.A.	-	1461	1461	0.39	-	~1	0.08	-	~0.1
16		1390	1383	1387	-0.61	-	~1	-0.4	-	~0.4
19	133.5mm	-	1560	1560	-	1.03	~1	-	0.72	~0.8
20	AL5083	1391	1387	1388	-0.64	0.84	~1	0.12	0.15	0.2

Table V : Summary of After Target Perforation Results and Analysis.

Round Number	Target Description	Penetration Duration (10^{-6} sec)	V_R Residual Velocity (M/sec)	Vertical Trajectory Component (Degree)	Vertical Yaw Component Degree)	L_R Residual Length (mm)	M_R Residual Mass (Gram)	Penetrator front Deformation	
								*H_f Length (mm)	**D_{Jf} Diameter (mm)
11	75mm	159	1342	-0.8	0.2	96	197	12	24
12	R.H.A.	239	1117	-3.1	22.9	65	117	12	19
13		350	215	7.7	-39	25	102	Plug P.L. 13	Plug P.D. 19
14	50.8mm	135	1405	-0.6	3.3	146	296	9	25
15	R.H.A.	163	1310	-0.5	7	129	255	10	20
16		182	1240	-0.8	1.8	130	259	9	23
19	133.5mm	244	1390	1.1	-4.3	138	303	10	23
20	AL5083	270	1218	0.1	0.4	136	270	14	22

*H_f - Length of forward end of penetrator that is subjected to appreciable plastic deformation.

**D_{jf} - Maximum diameter of plastically deformed forward end of projectile.

Table VI . Summary of Target Hole Dimension Measurements

Round Number	Target Description	Depth	Target Entrance Hole Average Diameter (mm) D_i	Target Exit Hole Average Diameter (mm) D_e	Exit Circumferential Fracture: *D_{fr} Average Diameter (mm)	Exit Circumferential Fracture: **P_{fr} Average Depth (mm)
11	75mm R.H.A		20	37	61	16
12			19	36	58(Partial)	11
13			20	37	49(Partial)	10
14	50.8mm R.H.A.		19	35	55	9
15			20	36	57	8
16			20	35	47	9
19	133.5mm AL5083	44.5	21	27	Ductile Exit	
		89	30	38		
		133.5	39	48		
20	133.5mm AL5083	44.5	19	22	Ductile Exit	
		89	27	34		
		133.5	37	39		

* D_{fr} - Maximum diameter of circumferential fracture region surrounding exit hole (circumferential avg.).

** P_{fr} - Depth from rear surface of circumferential fracture region surrounding exit hole (circum. avg.).

Striking Velocity 1461 M/Sec

Sample Round No. 15

Residual Velocity 1310 M/Sec

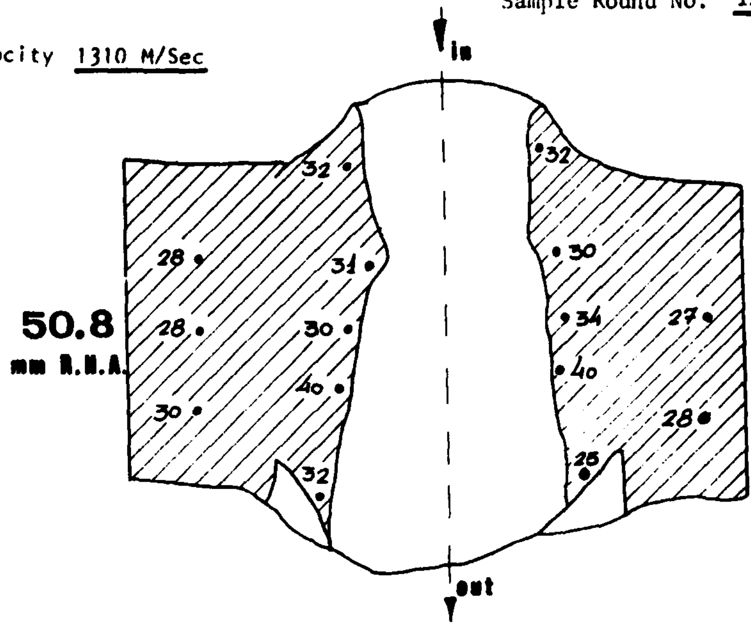


Figure 2 : Hole Profile After Perforation of 50.8 mm R.H.A Target and Hardness Test (HRc) Measurements.

Striking Velocity 1555 M/Sec

Sample Round No. 11

Residual Velocity 1342 M/Sec

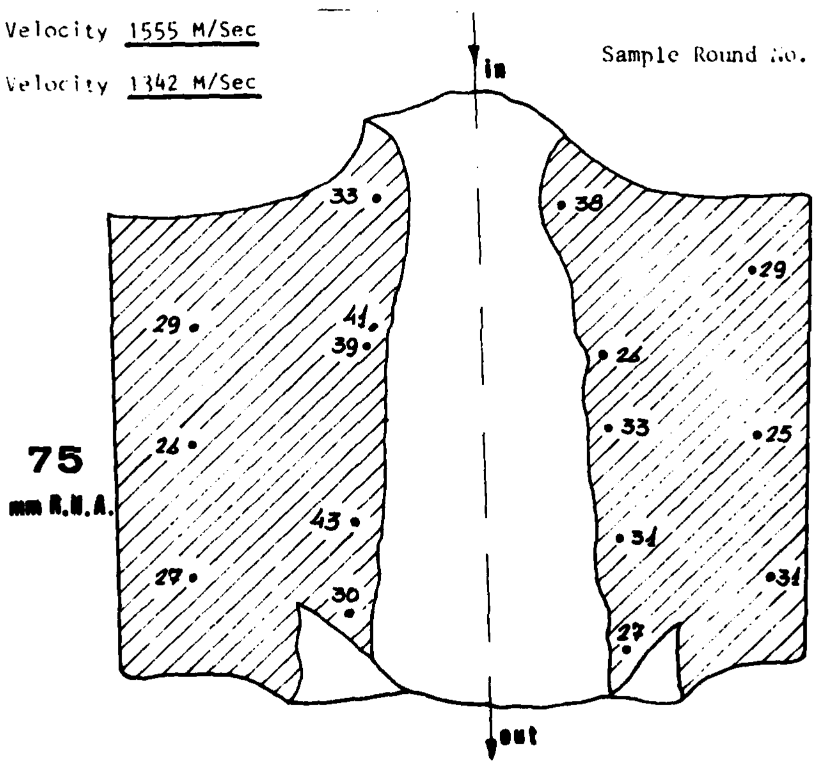


Figure 3 : Hole Profile After Perforation of 75 mm R.H.A. Target and Hardness Test (Rc) Measurements.

Striking Velocity 1560 M/Sec

Sample Round No. 19

Residual Velocity 1390 M/Sec

133.5 mm

AL-5083

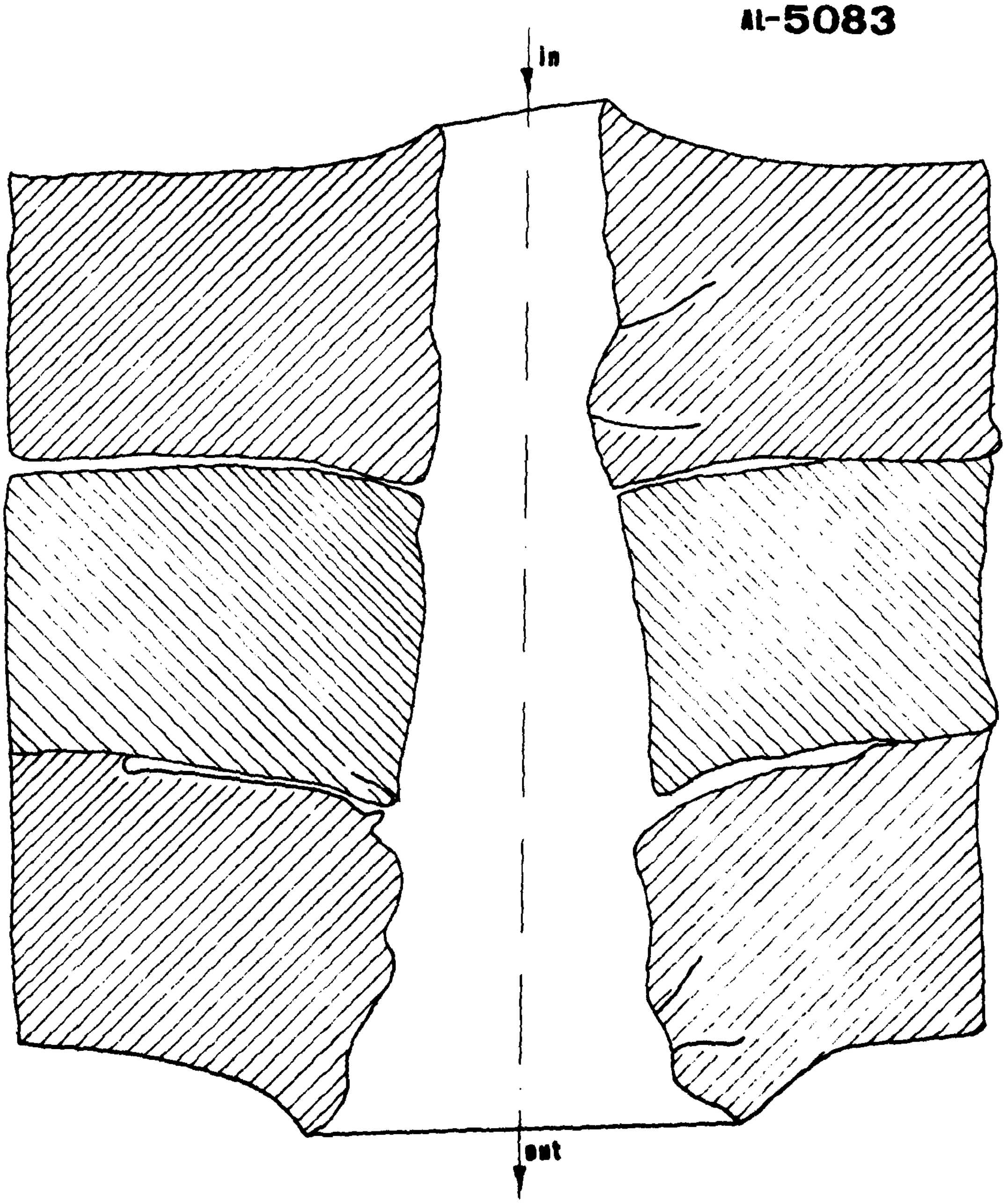
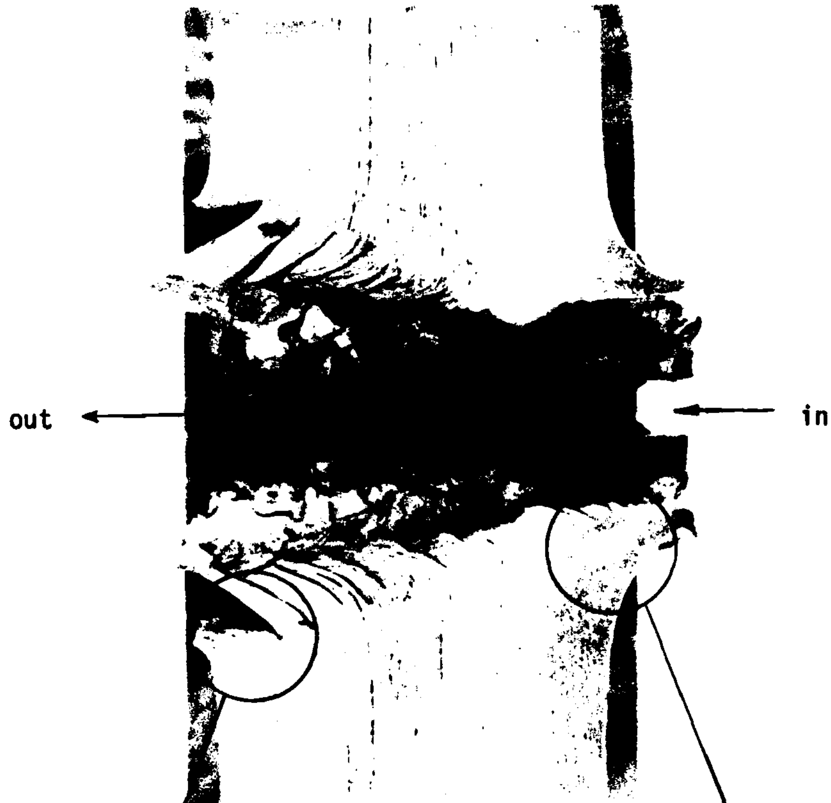
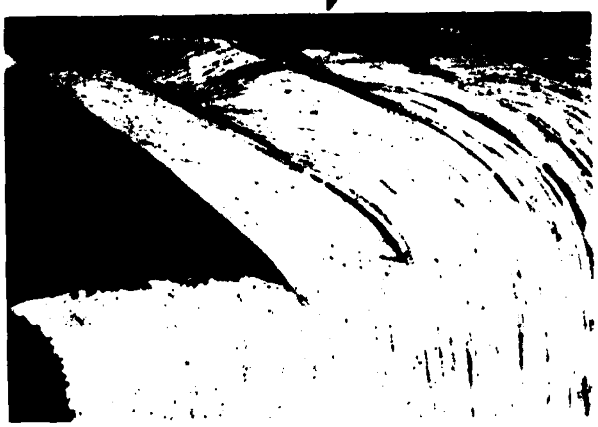


Figure 4 : Hole Profile, After Perforation of 133.5 mm AL 5083 H-115 Target (3 x 44.5 mm)



a. General view



b. Enlargement of exit region (x2.5)

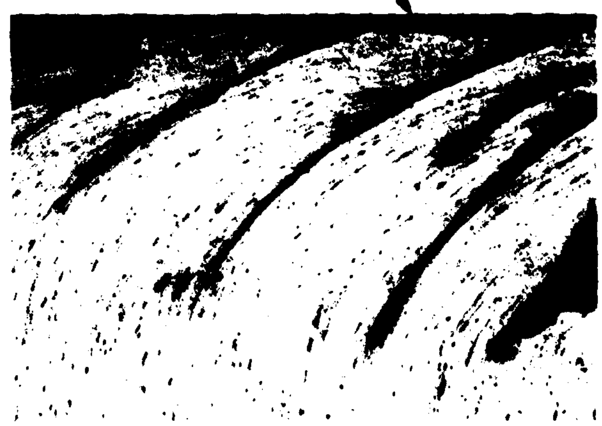
c. Enlargement of entrance region (x2.5)

Etching: boiling 50% HCl

Figure 5: Hole profile after perforation of 50.8 mm R.H.A. target. (Round No. 15; V_S = 1461 m/sec; V_R = 1310 m/sec; L_R = 129 mm)

a. General view

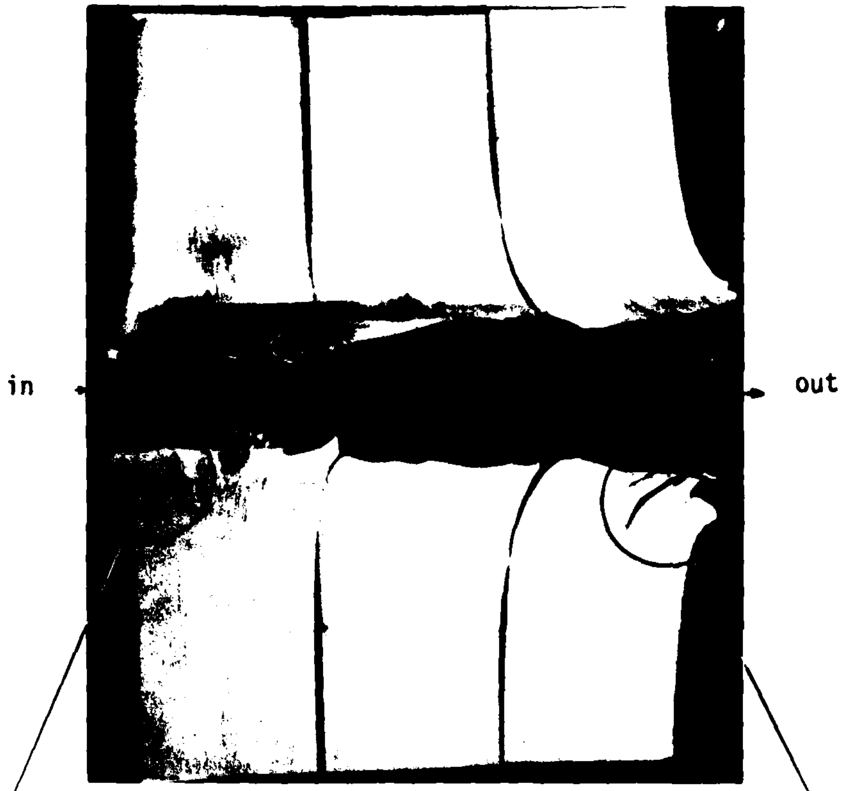
c. Enlargement of entrance region (x2.5)



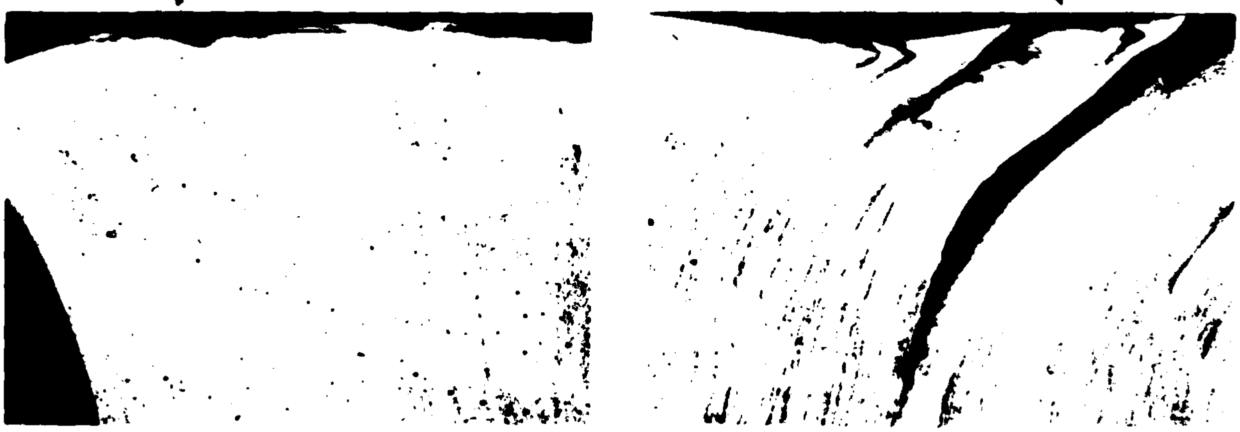
b. Enlargement of exit region (x2.5)

Etching: boiling 50% HCl

Figure 6: Hole profile after perforation of 75 mm R.H.A. target.
(Round No. 11; V_s = 1555 m/sec; V_R = 1342 m/sec; L_R = 96 mm)



a. General view

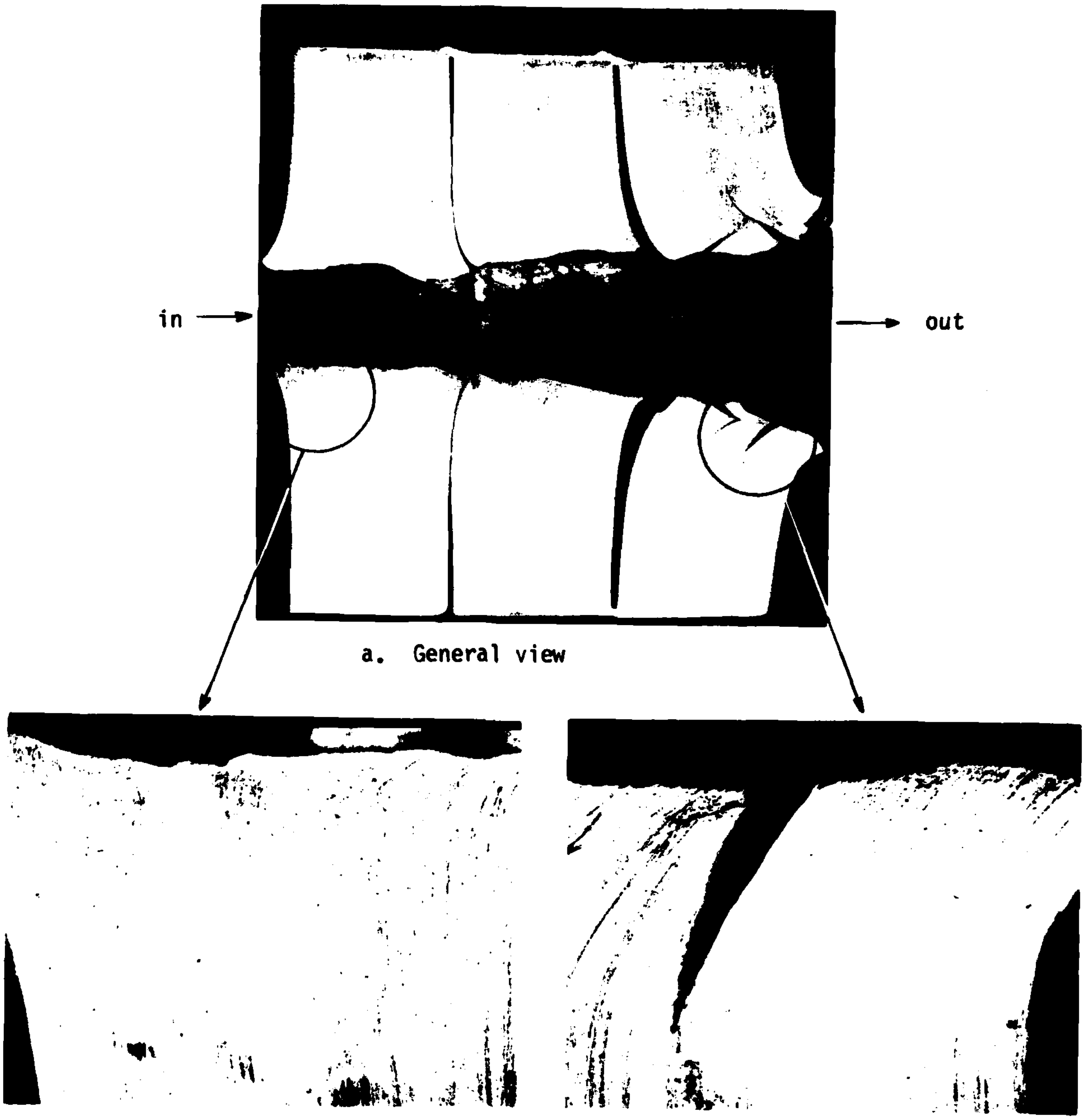


c. Enlargement of entrance region (x2.5)

b. Enlargement of exit region (x2.5)

Etching: Feric Chloride + HCl + Alcohol

Figure 7: Hole profile after perforation of 133.5 mm Al 5083 H-115 target. (Round No. 20; V_S = 1388 m/sec; V_R = 1218 m/sec; L_R = 136 mm)



a. General view

c. Enlargement of entrance region (x2.5)

b. Enlargement of exit region (x2.5)

Etching: Feric Chloride + HCl + Alcohol

Figure 8: Hole profile after perforation of 133.5 mm AL 5083 H-115 target. (Round No. 19; V_S = 1560 m/sec; V_R = 1390 m/sec; L_R = 138 mm)

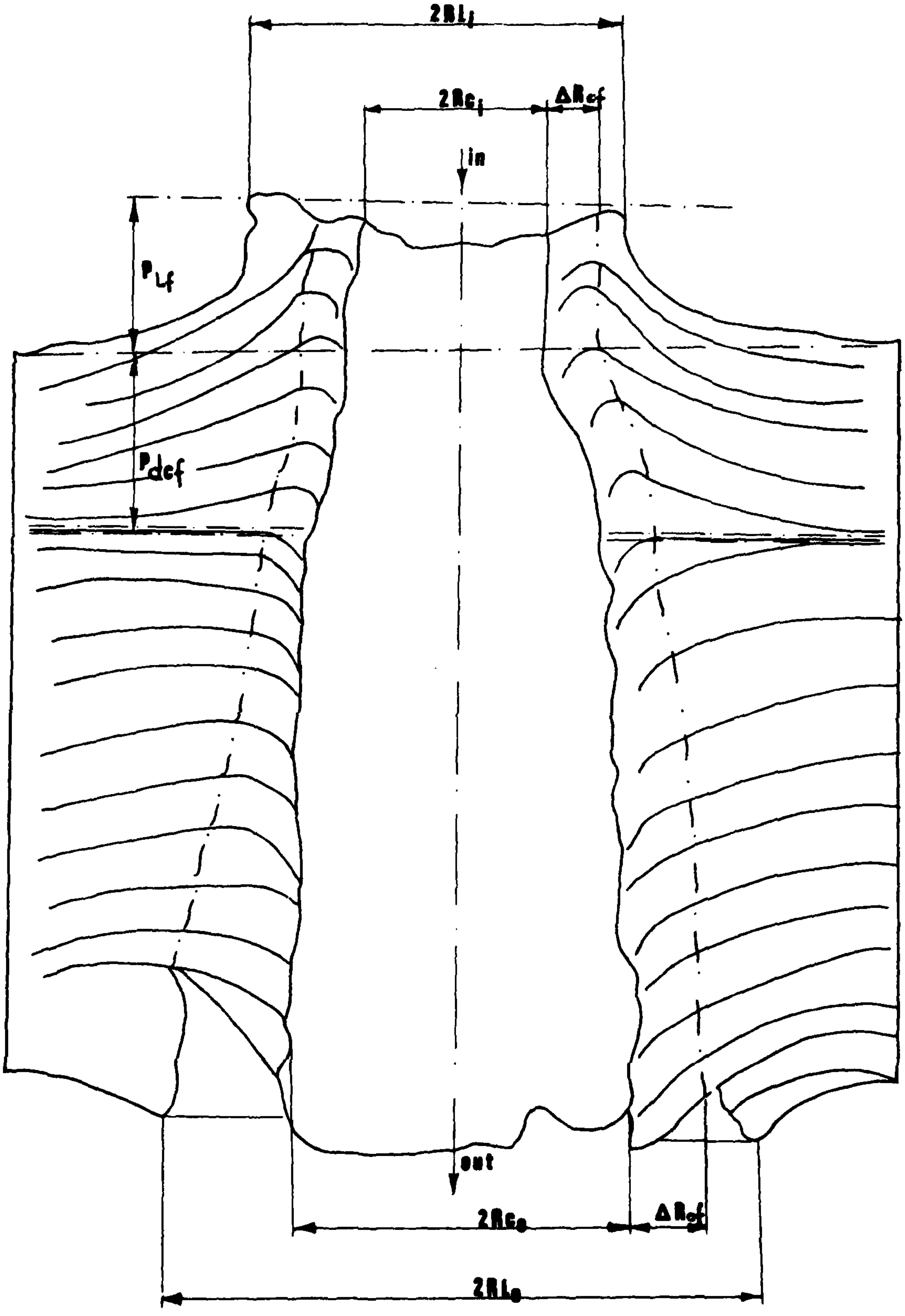


Figure 9 : Characterization of the Final Deformation and Hole Dimensions for Table VII.

Table VII: Characteristic Parameters Measured for Defining the Final Target Deformation.

Round Number	Target Description	Entrance Lips-P_{Lf} (mm)	Depth of Entrance Deformation-P_{dcf} (mm)	Radial Clearance for Sheared Regions (mm)	
				ΔR_{cf} Entrance	ΔR_{of} Exit
15	50.8mm R.H.A.	8.8 - 10.8	11.1 - 14.8	3.4	8.3- 8.4
11	75mm R.H.A.	9.0 - 12.1	13.4 - 15.9	3.5-4.5	10.4-10.8
20	133.5mm AL5083	7.8 - 10.4	17.8 - 18.0	5.1	12.6-14.1
19		9.5 - 11.5	19.9 - 20.7	5.8-6.5	11.6-12.9

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